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PAPER

Landowner decisions regarding utility-scale solar energy on working lands: a qualitative case study in California

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Abstract

Mitigating the predicted impacts of climate change requires rapid expansion of renewable energy production, including Utility-Scale Solar Energy (USSE) on an unprecedented scale. In the US, a significant share of planned USSE targets working lands—particularly farms and ranches—yet the decision factors informing private landowners' decisions to host USSE on their lands are little understood. Our research addresses this gap through a qualitative case study of working lands in California's San Joaquin Valley and San Francisco Bay Area, based on 60 interviews with farmers and ranchers, solar developers, and community and government organizations. Applying land system science and agricultural decision-making theory, we find that landowner decisions to host USSE are based on profit-maximization, water availability, visual and ecological landscape values, and agricultural land preservation ethic. Solar interest varies across landowner types, with farmers typically maximizing operational income while maintaining agricultural production, and ranchers often prioritizing lifestyle-related landscape benefits. The current feasibility of integrating solar with agriculture appears to be low beyond sheep grazing, with benefits and drawbacks discussed in detail. Optimal areas for future USSE development include farmlands with declining water availability, lands without permanent crops or high amenity value, and regions with energy-intensive agricultural operations. Study findings can inform state land use planning and community engagement by solar developers.

1. Introduction

To address the growing threat of climate change (IPCC 2021), renewable energy development is needed on an unprecedented scale (EIA 2019), including 300 GW of new solar in the US by 2030 to reach national renewable energy targets (Larson *et al* 2020). Achieving these goals requires both expansion of solar energy production in the built environment and Utility-Scale Solar Energy (USSE), or grid-tied facilities over 1 MW (Ong *et al* 2013, Sinha *et al* 2018). USSE is commonly installed on privately-owned working lands—lands actively managed for farming, ranching and forestry—especially on large cattle ranches and cultivated croplands (Beckman and Xiarchos 2013, Borchers *et al* 2014, Hernandez *et al* 2015).

As a land-intensive energy source (McDonald *et al* 2009), USSE requires vast areas of available land. Past studies have evaluated land availability for USSE using statistical and spatial modeling methods. GIS-based studies assessed land availability by accounting for limiting factors like transmission capacity, prime farmland, critical habitat, slope, public opposition, and legal protections (Butterfield *et al* 2013, Brewer *et al* 2015, Noorollahi *et al* 2016, Pearce *et al* 2016, Hoffacker *et al* 2017, Dashiell *et al* 2019, Guaita-Pradas *et al* 2019, Phillips and Cypher 2019, Wu *et al* 2019, 2020). Statistical, survey-based studies identified variables correlated with hosting solar facilities, including operational characteristics (Beckman and Xiarchos 2013, Borchers *et al* 2014), political affiliation (Carlisle *et al* 2014), and policies related to conservation, farmland protection, or renewable energy development (Delmas and Montes-Sancho 2011, Xiarchos and Lazarus 2013, Owley and Morris 2019). USSE development on public lands is constrained by various issues including public concerns about the potential negative impacts of solar facilities (Mulvaney 2017, 2019), leaving a notable knowledge gap: how landowner perspectives influence the availability of private lands for USSE. These unknowns are critical as nearly half of USSE in the Western US is expected to be developed on working lands (Wu *et al* 2020). Our case study assesses land availability by evaluating agricultural landowner ('landowner' hereafter) perspectives influencing USSE deployment based on a heterogenous interview sample of farmers and ranchers, as well as context-setting interviews with solar developers and other experts. We consider agriculture-USSE compatibility at the landscape scale as well as field-level integration with crop production or livestock grazing (often called 'agrivoltaics'). The research questions informing this study are:

1. What characteristics of landowners and operations are relevant to USSE development?
2. What benefits or drawbacks of USSE do different types of landowners perceive?
3. Under what conditions do landowners view solar development as compatible with agricultural production?
4. How might property management be secondarily influenced by the presence of or revenue generated by USSE?

2. Theory

To address these research questions, we draw on previous academic research into how agricultural landowners make decisions about adopting new interventions, including theory from land system science and agricultural decision-making.

2.1. Land system science

Ricardo's *land rent theory* (Ricardo 1821) from classical economics is often applied to explain land use decisions (Walker 2004, Angelsen 2010). Land rent theory predicts that land use will be allocated to activities generating the highest 'rent', or the value that a landowner draws from the land. The values that can inform land rent have recently been expanded to include ecological and socio-cultural values (De Groot *et al* 2002, Czyżewski and Matuszczak 2016). Based on this expanded notion of land rent, working lands are now considered multi-functional landscapes (Brummel and Nelson 2014) providing non-food benefits including tourism, energy, biodiversity, and employment (Renting *et al* 2009).

Drawing on land rent theory, several hypotheses can be formulated to predict land availability for USSE. Given that land rent in agricultural landscapes is typically a function of water access and soil quality, as factors critical to productivity, landowners may be more likely to host solar facilities if their lands have low or declining agricultural value or fertility and water constraints. This is supported by USDA survey data showing that California farmers with lower total value of production are more likely to host renewable energy (Beckman and Xiarchos 2013).

In the rangeland context, land rent is largely comprised of non-production values that may also influence land availability for USSE. Cattle ranches are notoriously low-income (Liffmann *et al* 2000, Wetzel *et al* 2012), making many ranchers receptive to income diversification opportunities (Cheatum *et al* 2011, Buckley Biggs *et al* 2021). Yet rangelands are also notable for providing non-production benefits valued by landowners, including wildlife, lifestyle, and cultural values (Gosnell and Abrams 2011). USSE may be constrained if perceived as conflicting with the amenity benefits and ecosystem services that motivate many ranchers to persist in ranching (Smith and Martin 1972).

2.2. Agricultural decision-making

Additional research from the field of agricultural decision-making has highlighted specific factors relevant to landowners hosting solar facilities, adopting sustainable practices, or engaging in conservation. Past studies have found landowners hosting energy facilities to be correlated with their energy costs (Beckman and Xiarchos 2013), operation size, debt, production-focus (Grout and Ifft 2018), agricultural incomes (Gazheli and Di Corato 2013), and availability of government subsidies (Bazen and Brown 2009). Community engagement by

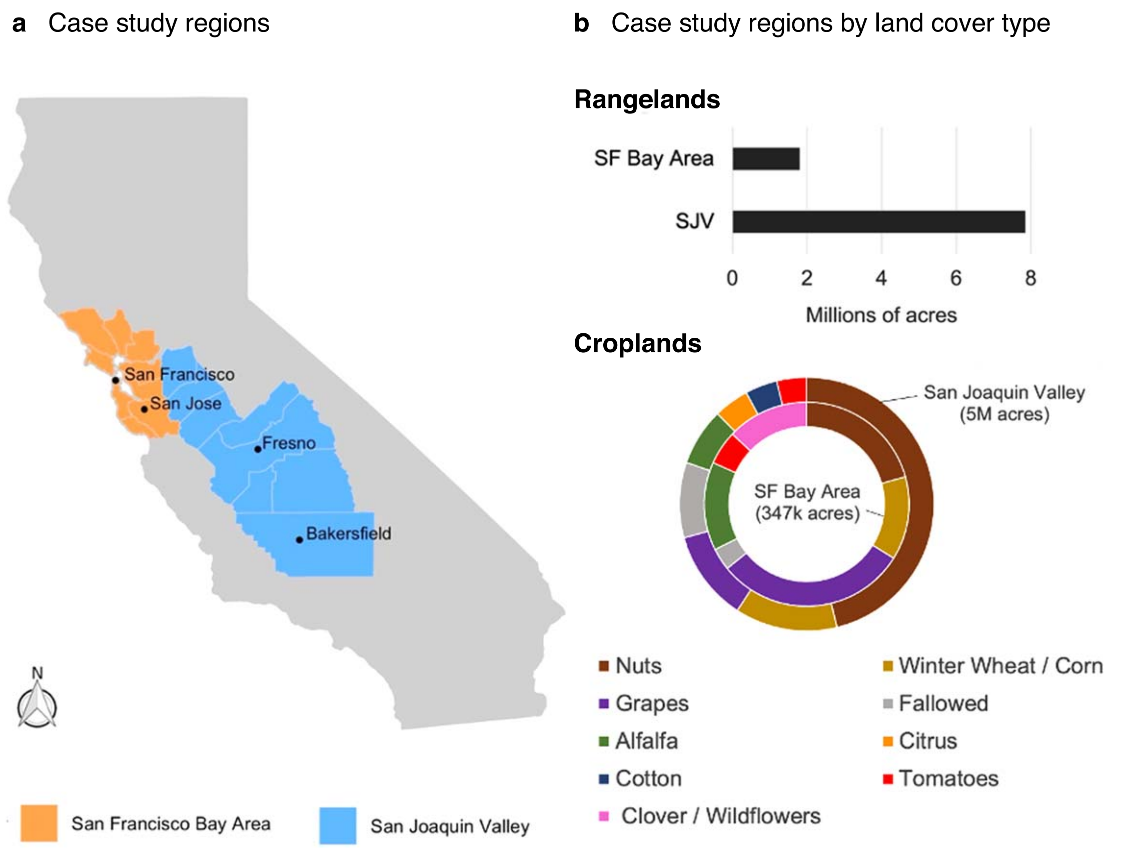

Figure 1. (a) Case study regions and (b) privately-owned agricultural land cover types by land area in the case study regions, including grazing lands, leading crops by acreage, and fallowed croplands. Data source: USDA CropScape 2020.

energy developers increases landowner willingness to host energy facilities (Syal *et al* 2020), while upfront costs can be a barrier (Xiarchos and Vick 2010). More broadly relevant to agricultural operations adopting sustainability practices, studies have found sustainability practice adoption to be correlated with program structure (Cheatum *et al* 2011, Mettepenningen *et al* 2013), management goals and attitudes (Lubell *et al* 2013), mental models (Hoffman *et al* 2014), perceived difficulty (Foguesatto *et al* 2020), dependence on operation income (Didier and Brunson 2004), and information access (Liu *et al* 2018), and also characteristics of the practices themselves like profitability and impact on productivity (Liu *et al* 2018, Mozzato *et al* 2018).

Based on this literature, we hypothesize that land availability for USSE is influenced by the following factors, which formed the basis of our interview protocol:

I. Institutional, market, and program factors (e.g., contract models, financing, policies, markets);

II. Farm and farmer characteristics (e.g., finances, experience); and

III. Motivations, attitudes, and perceptions (e.g., environmental perspectives, trust, perceived difficulty, long-term plans).

3. Materials and methods

3.1. Case study

The State of California has committed to achieving 100% renewable and zero-carbon electricity by 2045 (Senate Bill (SB) 100) and is the leading US state for solar capacity (Larson *et al* 2020). Up to 1.6 million acres of new USSE are needed to meet California's 2045 renewable energy goals (Wu *et al* 2019). Our study focuses on two California regions: the peri-urban rangelands of the San Francisco Bay Area (SFBA) and the croplands and rangelands of the San Joaquin Valley (SJV) (figure 1). These regions were selected for their USSE potential and high heterogeneity in land uses, commodities, and operation types.

Land availability for USSE in the case study regions may be influenced by state policies pertaining to groundwater, farmland, and habitat conservation. For example, California's Sustainable Groundwater Management Act (SGMA), requiring that prioritized groundwater basins cease groundwater overdraft, will

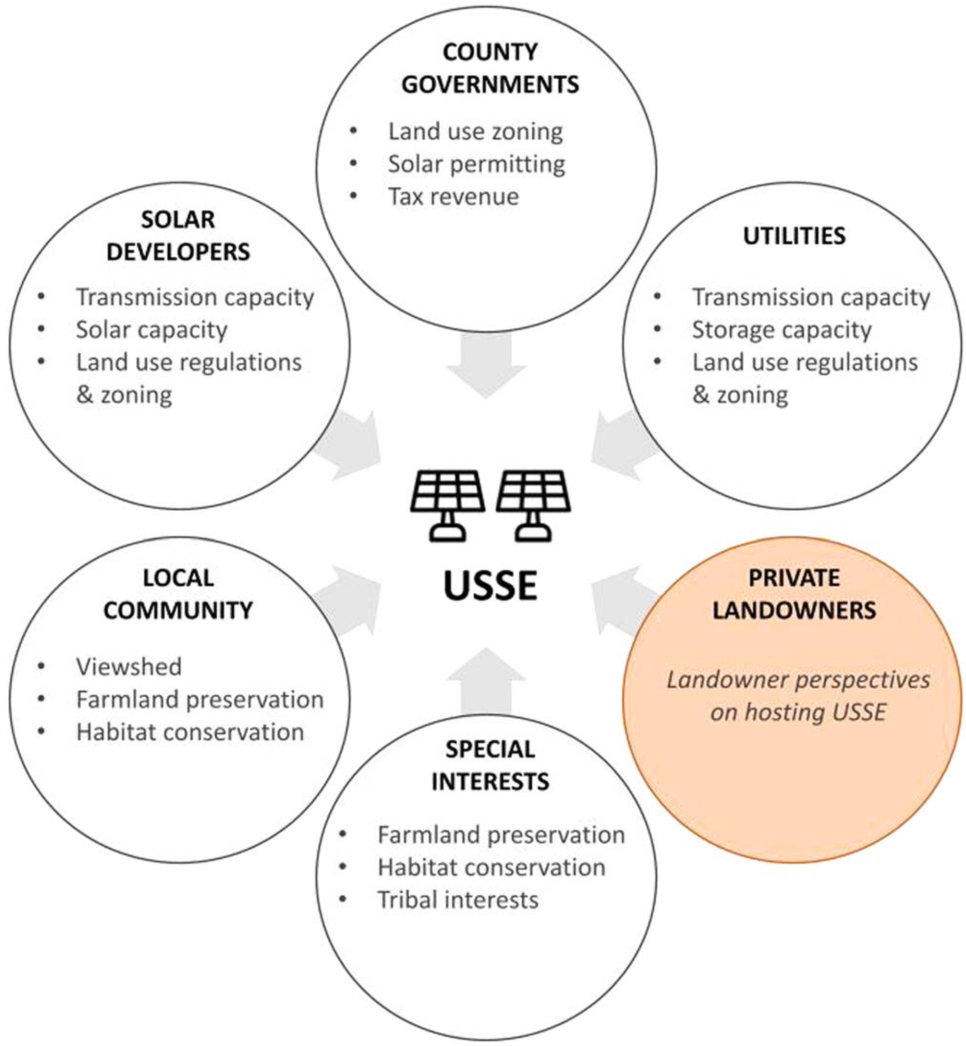

Figure 2. Sample decision factors relevant to key stakeholders of USSE deployment. This study assesses land availability as determined by private landowner perspectives (highlighted in orange).

cause an estimated 86,000 (Bryant *et al* 2020) to 200,000 ha (Hanak *et al* 2019) of irrigated croplands to be retired, increasing land availability. Alongside SGMA, California has developed a Multibenefit Land Repurposing Program (AB252), providing rental payments to SJV farmers for habitat restoration. While perhaps competing with USSE, such habitat restoration on fallowed farmland has local benefits for reducing dust and supporting biodiversity (Gardali *et al* 2021, Peterson 2021). Solar development may also be restrained by California's farmland protection program (the California Land Conservation Act of 1965 or 'Williamson Act') and conservation easements—which extinguish a properties' development rights—depending on local county and land trust restrictions (Wetzel *et al* 2012, Owley and Morris 2019). While USSE is often developed on rangelands due to their low monetary value, California's rangelands are also biodiversity hotspots (Myers *et al* 2000) providing abundant ecosystem services (Maestas *et al* 2003, Huntsinger and Bartolome 2014) that have been severely impacted by rangeland conversion (Cameron *et al* 2014). Environmental concerns regarding rangeland conversion may restrain USSE development in California.

3.2. Data collection and analysis

The research team conducted semi-structured phone interviews in 2021 (n=60) with stakeholders in three categories: landowners, community and government organizations, and solar developers (see figure 2; key landowner characteristics are summarized in table 1; see supplementary information 7 (available online at stacks.iop.org/ERC/4/055010/mmedia) (SI-5) for interview protocol). Rather than snowball sampling, we utilized purposive sampling to increase the heterogeneity of our sample across geography, landowner type, production systems, and solar experience. The Farm Bureau, commodity groups, UC Cooperative Extension, local land trusts, and farm media outlets were engaged to recruit diverse participants. Given this non-random sampling approach, our findings are not representative of the overall farmer and rancher population, but rather

Table 1. Interview participant details by category (n = 60).

Type	Count	Details	
Landowners	40	Geography	• San Joaquin Valley: 30 • San Francisco Bay Area: 10
		Operation type	Crops (n = 16): Nuts, olives, hay, wheat, citrus, grapes, row crops, nursery Livestock (n = 24): cattle/dairy/sheep
		Landowner type	• 21 livestock producers, 16 crop producers, 3 both • Mostly production-focused properties • 79% live and work on the farm/ranch for 6 + months/year • 82% reported that farming is their primary occupation • 58% of respondents had additional professions • All participants owned their properties; 37% rented additional land for agricultural activities beyond their own property
		Education (n = 37)	• 49% Bachelor's degree • 32% Graduate degree • 16% Associates/junior college degree • 3% High school
		Race (n = 39)	• 87.18% White • 2.56% Black • 5.13% Native American • 2.56% Hispanic • 2.56% N/A
Community & government organizations	11	• Commodity associations • UC Cooperative Extension • Agricultural lands solar experts • Farm Bureau • Conservation groups • Biologists (academic, government) • Resource management agency	
Solar Industry	9	• Solar companies • Solar developers & consultants • Community Choice Aggregators • Legal expert	

reveal the nuanced perspectives of the specific types of individuals and operations interviewed. Interview data were recorded and transcripts analyzed in NVivo 12, a Computer Assisted Qualitative Data Analysis Software. We analyzed transcripts using thematic analysis (Willig 2013) and the constant comparison method (Charmaz 2014), an analytical approach to interview analysis based on iterative hypothesis development (see SI-6 for thematic analysis codebook). To analyze the data, the coding team—consisting of the lead author and two trained research assistants—reviewed the initial transcripts together to develop a preliminary codebook based on themes raised by participants, distinguishing between codes pertinent to landowners, experts, solar industry representatives, or those shared across the groups. As additional transcripts were analyzed and coded, the research team discussed and agreed upon amendments and additions to the codebook as nuances or new topics emerged. Over time, some codes were combined where themes overlapped to the extent that distinction was not useful. Importantly, our coding was not case-focused, where the goal is to develop a complete story of a participants' lived experience, but rather issue-focused, where the goal is to identify patterns across participants.

3.3. Strategies to minimize biases

A common concern with qualitative analysis is ensuring consistent interpretation of interview data across researchers. To minimize potential interpretative discrepancies between coders, we engaged quantitative interrater reliability analyses during thematic coding, to assess 'the extent to which data collectors (raters) assign the same score to the same variable' (McHugh 2012). In the interrater reliability assessment, we maintained a preference for Type 1 errors over high kappa values to enable more nuanced coding. To address potential sample bias toward landowners with strong opinions on solar energy, we asked partner organizations to personally invite a variety of landowners to participate. The small sample size was deemed adequate as we achieved both inductive and *a priori* thematic saturation. While focused solely on two regions, our findings are relevant to other geographies with high solar capacity and farmland retirement.

4. Results

This section presents our findings regarding the hypothesized factors influencing land availability for USSE based on the literature: (I) institutional, market, and program factors; (II) farm and farmer characteristics; and (III) motivations, attitudes, and perceptions. Sub-sections represent themes included in our interview guide and codebook. Quoted interview participants are anonymously identified with 'P' (producer), 'S' (solar industry representative), or 'E' (expert) along with an identifying number. Factors constraining USSE siting on working lands, including those described in detail below, are summarized in table 5; distinct views across interviewed stakeholders regarding where USSE should be sited are summarized in table 6.

4.1. Institutional, market, and program factors

Our interviews revealed several approaches to hosting USSE on agricultural lands, each with unique benefits and risks. Beyond the characteristics of these opportunities, participants described the role of relevant policies potentially influencing their interest and ability to host USSE on their properties.

4.1.1. Models for USSE development

Participants described three models through which landowners can participate in USSE development: (1) customer-owned solar facilities, (2) sale of land, and (3) third-party owned solar facilities. Landowners choosing the customer-owned model, in which landowners buy and install solar panels themselves, explained that they prefer the larger income potential and operational autonomy. Others prefer to sell their land to avoid the hassle of site cleanup after the USSE facility is retired. Many solar developers also favor this model for its simplicity. Under the third-party owned solar model, developers lease land from landowners using Power Purchase Agreements, install and maintain the panels, and take responsibility for site cleanup. Many landowners reported having been approached by renewable energy developers for this purpose, particularly on properties adjacent to transmission infrastructure. Developers reported annual solar lease payments ranging from $100 to $2,000 per acre depending on location, averaging $1,000 per acre with a 20 to 30-year lease. Solar leases can be attractive to landowners who prefer not to finance or manage a solar array themselves, who see solar energy as outside their expertise, or who would like to keep the property in the family and consider USSE a temporary land use allowing for future agricultural activities after USSE retirement. Some landowners reported retaining water rights when selling land to enable irrigation of other lands.

Interviewed landowners had a variety of experience levels with hosting solar. 75% of landowners with experience hosting USSE ($n = 8$) had high interest in hosting additional USSE in the future, while those without USSE experience ($n = 32$) were more evenly split between low (56%) and high (44%) interest in hosting USSE. Many landowners emphasized the importance of financing, grants, and tax credits in making USSE feasible: 'I probably would be less inclined to put solar in if there wasn't that tax incentive.' (P26) When asked how they would dedicate potential income derived from USSE on their properties, landowners reported that they would generally use solar income to improve their operations. These improvements include developing water infrastructure and drilling wells to expand production capacity, improving grazing management, fixing roads and drainage systems, and better incorporating technology into their operations.

Landowners without solar experience cited several barriers, including financial risk due to uncertainties in energy markets, commodity prices, farm ownership transitions to the next generation, and perceived difficulty. While multi-decade contracts were familiar to landowners growing nut trees with similar lifespans, some dislike the long-term commitment: 'You can't tell me what the price for [energy] will be in 30 years. Here in California, we don't know what it is going to be next month.' (P31)

4.1.2. Multi-benefit planning policies

Complementary or alternative policies and programs can inform whether individuals engage with a specific opportunity like USSE. Some participants explained that policy-enabled, complementary income diversification opportunities would make the opportunity to host USSE more attractive, including income from groundwater recharge, conservation easements, Renewable Energy Credits, carbon offsets, and agricultural production. As an alternative to USSE, some landowners expressed interest in California's Multibenefit Land Repurposing Program. Landowner decisions to participate in that program would be generally based on potential profit, although environmental considerations play a role for some landowners: 'I would prefer to provide habitat than electricity.' (P25) This program would be most appealing to farmers with lands no longer viable for farming, as the program's rental rate is lower than what a landowner would earn from farming. However, cover-cropping may also be supported by the program and could be implemented without displacing agriculture. Relevant to this program, some landowners expressed concerns about removing lands from agriculture in perpetuity and whether the rental payment would be worth it unless combined with other opportunities.

Table 2. Average annual revenue per acre for rented agricultural land and leading commodity types in California, based on 2019 yield and price data. Data source: California Agricultural Statistics Review 2019–2020 (CDFA 2020).

Sample farmland rental types	Annual Revenue ($/acre)[a]
Solar lease	$1,000
Irrigated croplands	$543
Pastureland	$13
Sample commodities	**Annual Revenue ($/acre)**
Mandarins	$10,623
Table Grapes	$8,040
Pistachios	$6,707
Almonds (shelled)	$5,249
Processing tomatoes	$3,925
Walnuts (in shell)	$3,526
Alfalfa	$1,456
Corn (for sileage)	$1,250
Cotton (upland)	$831
Other Hay	$589
Winter Wheat	$297
Oats	$180

[a] Solar lease rate is the typical rate described by interviewed solar developers, which can vary significantly depending on the location and parcel size. Listed commodity revenues do not account for costs associated with each activity (e.g., farm production expenditures such as labor, fuels, chemicals, fertilizer, feed, etc).

4.2. Farm and farmer characteristics

This section explores the characteristics of landowners and their operations that may influence land availability. Based on our interviews, solar energy can provide an attractive, alternative source of stable income to agricultural operations, a particularly valuable opportunity in the context of rising power costs, increasing income volatility, and uncertain water access.

4.2.1. Crop farms

Given the burden of rising energy costs, operations with high energy bills have been early adopters of solar energy, including those using groundwater pumping or drip irrigation, processing (e.g., shelling almonds, processing tomatoes), or cooling livestock (e.g., dairies). Participants reported annual energy cost reductions from solar energy ranging from tens to hundreds of thousands of dollars. Income from USSE can also mitigate volatility in agricultural income, which landowners reported being often delayed, unpredictable, or infrequent. Solar energy can be particularly important for those dependent on volatile income as a primary income source; more landowners expressed high interest in hosting USSE who depended on agricultural income as a primary income source (50%) than those not dependent on agricultural income (33%) (SI-2, SI-4 table 2(a)). For many landowners, solar energy production improves land rent: 'It's a great way to create value out of a dormant resource.' (P24) For operations facing declining water access, solar income can enable landowners to purchase other lands with better water access or reallocate water to other land, supporting the long-term economic viability of agricultural operations.

While solar energy can benefit landowners, co-location of solar energy and agriculture in rural landscapes also introduces challenges. Without pest removal, solar arrays can become host to rodents that impact neighboring farms. To address this challenge, USSE facilities often engage full-time groundskeepers and pay for rodent removal. As one participant explained: 'We are basically sterilizing the environment underneath the solar panels to keep the operation and maintenance costs at a reasonable level.' (P9) While studies have explored methods for improving wildlife habitat under USSE (Moore-O'Leary *et al* 2017, Semeraro *et al* 2018, Sinha *et al* 2018), the extent to which USSE impacts neighboring farms by harboring pests is unknown. Experts reported that solar developers typically follow local guidelines for rodent control as required by county solar permits. Another concern raised by participants is agricultural dust impacting solar panel productivity, particularly during almond harvest. Despite dust removal costs, landowners and developers described successfully blending USSE with nut cultivation in the SJV.

Some participants expressed interest in field-level integration of USSE and agriculture on their properties (or 'agrivoltaics') based on benefits from shade, reduced heat damage to crops, and increased water availability for crops by capturing fog moisture. However, interviewees highlighted several concerns, including accessibility for employees and vehicles during harvest. Landowners also highlighted the importance of adequate solar radiation being transmitted to crops to maintain yields, and potential issues with irrigating pasture under USSE. From the perspective of solar developers, while integrating agriculture into USSE can increase community acceptance, agrivoltaics can also significantly increase management complexity and cost. Some experts also expressed concerns that agrivoltaics might decrease land use efficiency by expanding the solar-agriculture interface and corollary tensions between energy production and agriculture.

4.2.2. Rangeland operations

Counties often prioritize rangelands for USSE due to their low economic value, with solar facilities generally displacing grazing activities. However, while less common for vegetation management than gravel or mowing, sheep grazing has been integrated into some solar facilities, particularly to increase public acceptance of USSE. Cattle grazing has not been integrated into USSE in California, although one developer is in the process of permitting a facility incorporating cattle grazing in the SFBA.

Interviewees identified several benefits of grazing livestock under USSE: landowner income diversification, avoided damage to solar panels from flying rocks dislodged by mowers, improved habitat quality, reduced herbicide usage, and maintaining ranch lifestyle values. Ranchers also predicted animal welfare benefits from shade provided by USSE in areas lacking tree cover. Some ranchers would only host solar arrays if they could continue to graze their livestock under the panels, highlighting potential land availability for USSE if facilities are built to be compatible with livestock grazing.

Most USSE facilities forgo cattle grazing due to concerns around increased cost, liability, and animal welfare. To accommodate livestock grazing, solar facilities need to protect exposed wires, and raise panels and create sturdier posts for cattle—increasing construction costs. Damage to wiring from livestock can be significant: 'On a 200-acre site, if we have sheep come through and graze, we might see as much as $30–40,000 worth of damage.' (S3) Some participants raised safety concerns regarding high-voltage infrastructure and third-party presence on operations. Other concerns include feed quality under solar panels, water access for livestock, potential risks at different life stages for livestock, and potential limitations to cattle movement.

4.2.3. Water availability

USSE typically competes with agriculture, particularly in the highly productive SJV. Yet SJV farmers are increasingly experiencing water shortages due to drought and SGMA, forcing them to prioritize certain parts of their operations for cultivation. Landowners who fallow land due to water shortages typically remove row crops to divert water to higher-value, permanent crops. During our interviews in summer 2021, SJV farmers were removing viable but older nut trees to divert limited water resources to younger trees. Given the role of water constraints in land fallowing, one SJV farmer explained: 'What is taking prime farmland out of production is not solar, it is the lack of water.' (P39) Given this, water availability can be understood to be a constraint on land availability for USSE, and conversely, lands experiencing water constraints are more likely to become available for solar energy development.

4.2.4. Land characteristics

Landowners interested in USSE indicated that they would dedicate 5 to 10% of their lands for solar energy generation on average. For this decision, landowners evaluate the relative income potential of each field, accounting for future water accessibility. Generally, landowners implement USSE where solar income is greater than agricultural income, making solar energy less attractive on lands with permanent crops given their higher revenue potential, fixed costs, and higher margins (see table 2 for annual revenues per acre of rented agricultural land and commodities). Landowners generally select the lowest value portions of their properties for USSE—as one farmer explained, 'My worst ground.' (P22) Landowners with both croplands and rangelands typically prefer to place USSE on rangeland given the lower income potential of grazing lands. That said, some landowners consider rangelands to be natural landscapes and thus a worse fit for USSE given the non-tangible, lifestyle values that would be displaced by solar panels.

From the perspective of solar developers, the ideal lands for USSE are flat or up to 5% slope. This can be challenging on rangelands due to their topography, although one company interviewed utilizes a panel technology compatible with slopes of up to 15%. Developers prefer to develop USSE on larger properties due to economies of scale.

4.3. Motivations, attitudes, and perceptions

Our interviews revealed two factors that reduce landowner interest in hosting USSE: landscape values and agricultural land preservation ethic. Community acceptance and perspectives on climate change appear to be relevant but not primary factors in USSE decision-making.

4.3.1. Landscape values

USSE impacts on visual and ecological landscape values concerned many participants, particularly for rangelands. In fact, some interviewed landowners had chosen not to engage with solar developers in the past because USSE did not fit within their vision for the land. As one developer described: 'There is lots of trenching usually involved at these facilities with wires underneath the ground. It is going to be plowed up, it is going to be torn apart.' (S3) Solar developers commonly manage liability by removing vegetation, grading, using weed cloth and gravel, sterilizing soils and applying herbicide. Such activities, while aimed at preventing fire-risk and shade from vegetation, essentially eliminate habitat value (Macknick *et al* 2013). Participants described feelings of sadness: 'The way they're putting solar in now is downright criminal in the way it covers up the landscape, the way it converts it.' (P10) Interviewed experts expressed strong concerns about the impact of USSE on the state's remaining rangelands: 'Solar should go on croplands since they are going to be challenging to restore to habitat. Most of the rangeland is pretty decent wildlife habitat.' (E9)

Participants also expressed concerns about viewshed impacts, particularly prevalent among ranchers who prioritize property amenity values over production value: 'It's just not what I would want on our family ranch … we enjoy the pristine nature of that whole environment.' (P3) Absentee landowners expressed greater interest in hosting USSE than those living full-time on their farm or ranch (SI-2, SI-4 table 2(b)), likely due in part to the reduced viewshed concerns of those living elsewhere. A strong majority (94%) of crop farmers consider profit a key factor in USSE decisions compared to livestock producers (67%), while more livestock producers take environment and viewshed into account when considering USSE (figure 3).

As expected given the unique peri-urban setting and development pressure of the SFBA, SFBA and SJV ranchers participating in our study regarded land use differently. SFBA ranchers expressed less interest in hosting USSE, with only 38% stating high interest in hosting USSE compared to 54% of SJV ranchers. Most SFBA ranchers (63%) shared concerns regarding the viewshed impacts of USSE, compared to a minority (31%) of SJV ranchers (table 3).

4.3.2. Agricultural land preservation ethic

Many landowners and experts shared concerns about USSE displacing agricultural production: 'The [SJV] is absolutely the most productive agricultural land on planet Earth … Once you pave it over, you lose it forever.' (E6) Some participants believed that it would be difficult to revert to agricultural production after solar development. Most farmers and ranchers considered agriculture their top priority and wanted to continue agricultural activities even if they hosted USSE, with solar panels placed on a small portion of their lands. For ranchers, low-slope lands most viable for USSE were often the most useful for livestock management activities, reducing interest in solar energy production on those lands.

4.3.3. Community acceptance

Most landowners dismissed the influence of their communities on their decisions around USSE, beyond bringing the opportunity to neighbors' attention: 'I don't really care what other folks are doing that much.' (P12) Trust of solar developers did not appear to be an important factor in the landowners being open to a third-party solar contract—as several participants said, 'Trust but verify.' (P13) That said, local concerns about the appropriateness of USSE on working lands can be a barrier to permitting. County permitting of solar facilities on agricultural lands and prime farmland varies significantly across regions and is determined by local counties. Beyond county regulations, several solar developers also cited conflicting utility interests: 'Edison, PG&E, and San Diego Gas & Electric do everything they can to prevent solar from being developed.' (S8)

4.3.4. Climate change perceptions

Belief in anthropogenic climate change and whether USSE could mitigate climate change varied significantly across participants. Most landowners with high interest in hosting USSE also accepted the scientific consensus on anthropogenic climate change and found the idea of producing clean energy for local cities appealing; however, half of landowners who accepted the scientific consensus on anthropogenic climate change expressed low interest in hosting USSE (see table 4 for details). Such variation in solar facility interest can be explained by the decision factors discussed above, where landowners who support solar energy as a climate solution may oppose hosting or living adjacent to USSE due to competing landscape values.

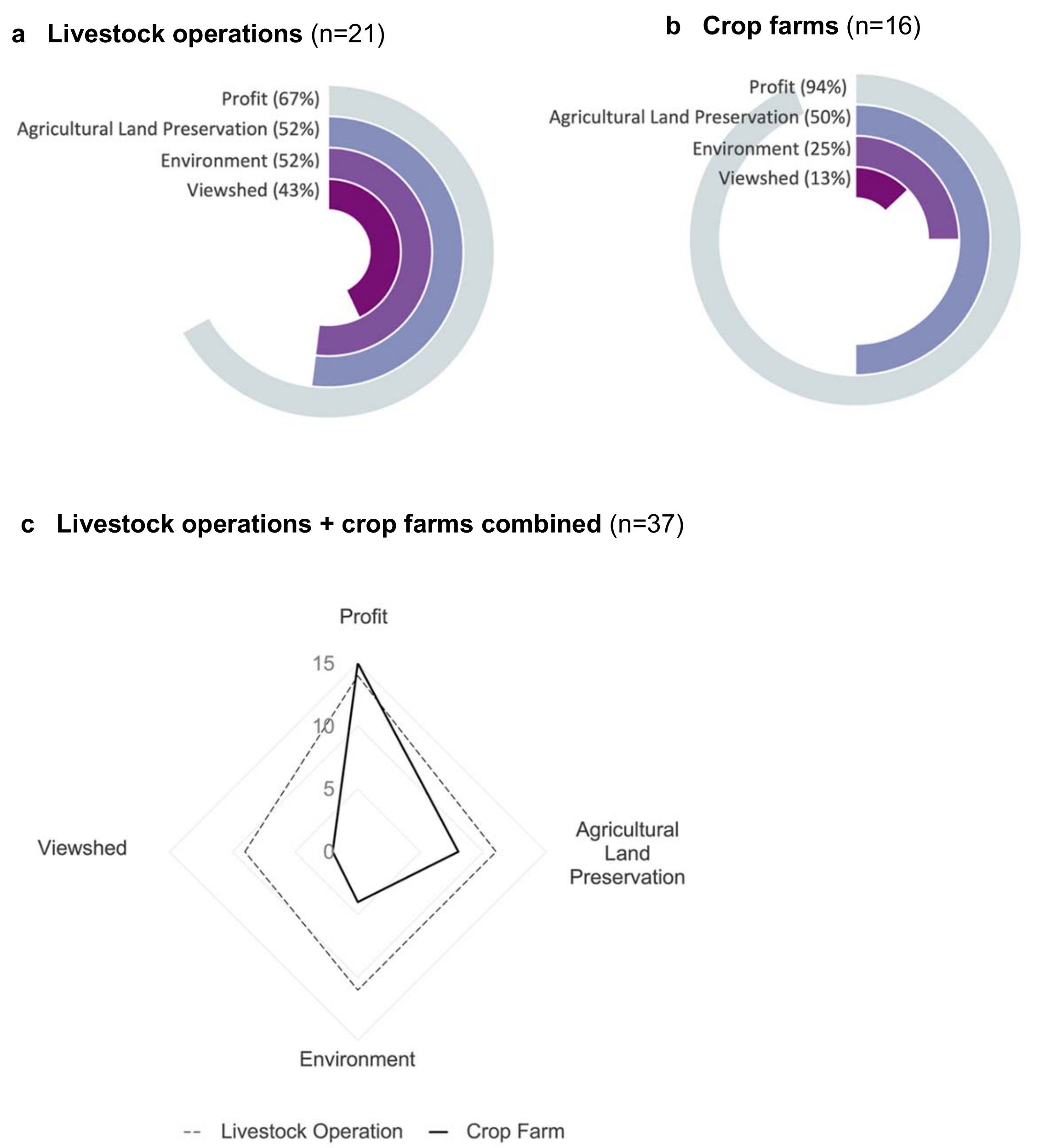

Figure 3. (a) Percentage of ranchers who mentioned specific USSE decision factors, (b) percentage of crop farmers who mentioned specific USSE decisions factors, and (c) number of interviewed landowners prioritizing specific decision factors relevant to hosting USSE, by operation type. Note: 3 operations that raised both livestock and crops are not shown.

5. Discussion

Based on our findings, it appears that optimal areas for future USSE development include operations with declining water access, fewer permanent crops, fewer amenity benefits to the landowner and society, and high energy intensity. These findings are in contrast to previous studies that prioritized ranches, properties with internet access, and newer farms for future USSE development (Beckman and Xiarchos 2013, Borchers *et al* 2014). The different conclusions of our study compared with previous USSE research likely derive from our interview-based approach, which allowed for the consideration of variables not integrated into previous studies that were limited by the types of variables measured in surveys. The new variables our work highlights include water constraints, landscape values, and the fixed costs associated with permanent crops. Importantly, our methodological approach allowed for consideration of ongoing or expected changes that may influence land decisions, such as recent and expected land fallowing in the Central Valley due to water constraints. Such trends may not appear in snapshot approaches to characterizing operations based on variables like current productivity or profit.

Revisiting our finding that trust of solar developers does not appear strongly relevant to landowner decision-making, it may be helpful to distinguish between the importance of trust related to environmental interventions

Table 3. Landowner concern about viewshed impacts of USSE by operation type & region.

	Viewshed Concern			
	Not Concerned	Concerned	Total	N
(a) Concern about viewshed impacts by operation type				
Livestock	57% (12)	43% (9)	100%	21
Crops	88% (14)	13% (2)	100%	16
Livestock + Crops	100% (3)	0% (0)	100%	3
Total				40

(b) Rancher concern about viewshed impacts by region	Viewshed Concern			
	Not Concerned	Concerned	Total	N
SFBA	38% (3)	63% (5)	100%	8
SJV	69% (9)	31% (4)	100%	13
Total				21

Note: (a) 13% of crop farmers were concerned about the viewshed impacts of USSE, compared with 43% of livestock operators. (b) Ranchers in the peri-urban rangelands of the SFBA expressed more concern about viewshed impacts of USSE than those in the SJV.

Table 4. Landowner climate change perspectives & interest in hosting USSE.

	Interest in Hosting USSE		
	Low Interest	High Interest	N
(a) Interest in hosting USSE by acceptance of climate science			
Does Not Accept Climate Science	50% (10)	33% (6)	16
Accepts Climate Science	50% (10)	67% (12)	22
Total	100%	100%	38

(b) Interest in hosting USSE by appeal of producing clean energy for local cities	Interest in Hosting USSE		
	Low Interest	High Interest	N
Not Appealing	35% (6)	0% (0)	6
Appealing	65% (11)	100% (15)	26
Total	100%	100%	32

(c) Acceptance of climate science & appeal of producing clean energy for local cities	Appeal of producing clean energy for local cities		
	Not Appealing	Appealing	N
Does Not Accept Climate Science	67% (4)	44% (11)	15
Accepts Climate Science	33% (2)	56% (14)	16
Total	100%	100%	31

Note: Interest in hosting USSE at levels 1–5 was categorized as 'low', and levels 6–10 as 'high.' Whether landowners found the idea of producing clean energy for local cities appealing was coded with a binary 'yes' or 'no' based on their responses. Relating to climate perspectives, the code 'does not accept climate science' was used for participants who do not accept the scientific consensus on climate change, and 'accepts climate science' for those that do accept it.

that bring income benefits compared to those without. For example, Tanguay *et al* (2021) found trust to be a critical factor in whether environmental organizations are able to influence landowners' management practices, particularly practices relevant to wildlife and biodiversity. In these cases, landowners may fear that engaging in such programs could reduce their operations' viability, as documented in the case of rangeland conservation easements (Buckley Biggs 2022). In contrast, landowners likely do not perceive the opportunity to host USSE as

Table 5. Constraints on USSE development on working lands across three categories.

Constraints (# mentions)	Sample quotes	Solutions[a]
I. Technical constraints		
Battery storage (8)	'We don't really want any more deliveries during the middle of the day.' (S1)	Increase battery storage
Transmission & distribution (7)	'The most important policy thing would be improving transmission lines.' (S8)	Transmission development
		Distributed energy resources
Farm size (5)	'Somebody that's farming 1,000 acres is probably more likely to qualify … that constricts the ability for somebody to get into renewables.' (P22)	Aggregate agricultural properties
Slope (5)	'I'd say that the 5% is definitely the threshold that we use in mapping.' (S2)	Technological development allowing for USSE on steep slopes
II. Policy constraints		
Land preservation policies (18)	'The Board of Supervisors raised the issue of the fact that it was a Williamson Act parcel…' (P8)	Improve USSE-ag compatibility
	'Almost all the ground out where we are is under Williamson Act contract, and so getting out of that is a real pain.' (P5)	County policies that consider USSE compatible with the Williamson Act
Local permitting (12)	'Five years to get the habitat conservation plan and the incidental take permits is a long time.' (E5)	Streamline local processes
	'The permitting process was a nightmare…' (P25)	
Utility interests (8)	'Edison, PG&E, and San Diego Gas & Electric do everything they can to prevent solar from being developed.' (S8)	Improving USSE profitability for utilities
III. Socio-economic and environmental constraints		
Agricultural land preservation (25)	'I think that there should be a concern if a solar array is going to take away a highly productive, working land area.' (E7)	Improve USSE-agriculture compatibility
Viewshed impacts (12)	'It's just not what I would want on our family ranch… we enjoy the pristine nature of that whole environment.' (P3)	Improve USSE-agriculture compatibility
		Avoid lands with high environmental value
Financial risk (11)	'It's the high cash outlay… we're not sure we're going to be able to be farming in 10 or 20 years.' (P21)	Landowner education
		Low-cost financing
		Solar leases
		Multi-generation engagement
Water availability (9)	'Hundreds of thousands of acres will be fallowed in the Valley where there's no alternative. Then [USSE] income is certainly more attractive than zero.' (P1)	Prioritize regions with expected water constraints for USSE development
Dust concerns (9)	'The worst dust problems are coming from the almonds in the San Joaquin Valley. That's notorious for producing huge amounts of dust.' (E11)	Community & landowner engagement by solar developers
Perceived difficulty (9)	'Anything of that magnitude, it's got to be pretty complex.' (P2)	Landowner education
		Peer-to-peer learning networks
Habitat impacts (8)	'What people don't realize is that solar arrays are highly disruptive to the ground, the soil and ecosystem.' (P2)	Avoid lands with high environmental value Improve habitat quality of USSE
Community acceptance (8)	'Where do people go ? Where do people hunt ? If you are a thoughtful developer, you are gathering information from people in the area so you can figure out where to be and where not to be.' (S4)	Community & landowner engagement by solar developers
Pest concerns (5)	'Inactive management attracts different animal species on farms that are dangerous.' (E2)	Enforce pest management

[a] Listed solutions were developed by the research team based on issues highlighted during interviews by landowners, solar developers, or experts.

one which would limit agricultural viability, but rather as an opportunity to improve their business through income diversification. It is perhaps for this reason that interviewed landowners viewed interactions with solar developers as a business transaction more than a partnership requiring trust.

Table 6. Perspectives on solar siting across interview participants: where should USSE go?

	Where land is available	Where it avoids displacing ecosystem services	Where profit is maximized
Solar developers	*Where the community accepts it:* 'A project slated to get built in Napa just went down in flames because the community was against it…' (S1)	*On impacted lands:* 'We try as much as possible when it's feasible to use lands that are either contaminated or otherwise degraded, are on retired agriculture, and don't have impacts on threatened and endangered species.' (S6)	*On low-slope lands:* 'You have to do all this very efficiently to be able to stand the pricing… I think that 5 or 10% slope is quite tolerable with the new trackers.' (S8)
Landowners	*On water-constrained lands:* 'On a strictly revenue per acre type calculation analysis, we can make more money by planting pistachios [than solar]. But the big difference is, it takes water to grow those pistachios.' (P5)	*Avoiding environmental impact:* 'The cattle ranch is wilderness. On the farm, it's already disturbed — I'm not concerned about the environmental impact.' (P1)	*Where solar income is greater than agricultural production income:* 'Whether I look at a solar panel or an almond tree, I don't care. As long as one makes more money than the other one, that's the one that's going to be there.' (P17)
		Avoiding viewshed impacts: 'I am highly opposed to large scale solar panels on rural landscapes or ranches for the environmental impacts, viewshed …' (P36)	*On operations with high electric bills:* 'Our demand for electricity went way up when we started converting to drip and so the solar panels have really helped that…' (P25)
Community & Government Organizations	*On water-constrained lands:* 'A majority of land in the county that has been more ripe for solar has been these farms that we would call white areas… a piece of property that doesn't come into an irrigation district's jurisdiction. That's a person who probably has no access to surface water rights and is only pumping.' (E2)	*Avoiding rangelands:* 'Rangelands are more suitable for conservation easements, because they're generally less disturbed. Why further disturb marginally disturbed land?' (E5)	*Where there is transmission capacity:* 'The cost of transmission from the facility to the substation per mile is so extraordinarily expensive that even three miles is a stretch.' (E6)
		Avoiding agricultural lands: 'Some of the best ag lands in California have been paved over by cities, so I think that there should be a concern if a solar array is going to take away a highly productive, working land area.' (E7)	*Where solar income is greater than agricultural production income:* 'Solar only takes place where it makes economic sense.' (E3)
			'Range cattle and dryland farming look less productive because down the agricultural value chain, there are fewer jobs involved in that than active farming, packing houses, those types of higher value crops.' (E11)

This study highlights the importance in USSE siting of both water policies like SGMA and private working lands. SGMA's role in increasing land availability for USSE could reduce energy development pressure on rangelands, therefore also reducing the environmental impact of USSE (figure 4). If future USSE development takes places in the optimal locations identified by our study, rather than on the types of operations that have adopted USSE based on previous research, the environmental impact of USSE—and potential barriers to expansion—may be avoided. The landowner interest in USSE documented in this study highlights the importance of private lands in achieving renewable energy targets, augmenting past research into USSE on public lands (Mulvaney 2019).

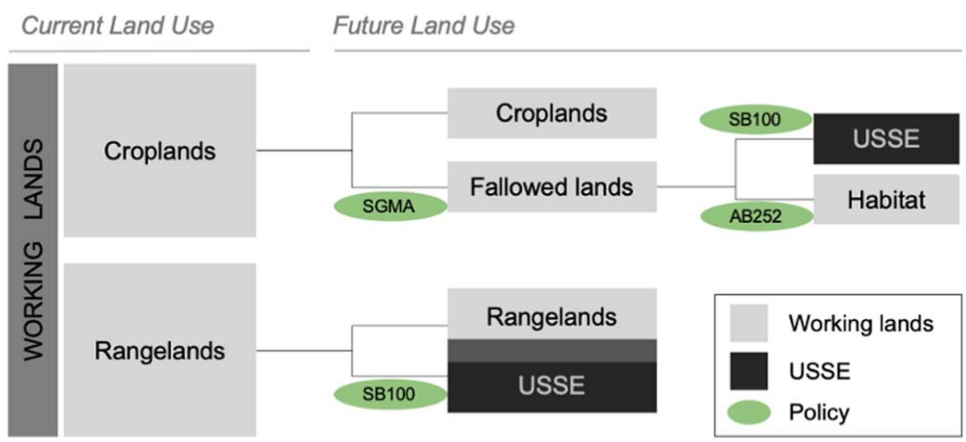

Figure 4. Land use transitions on California's working lands. State energy, water and conservation policies drive land fallowing and energy development on California's working lands. Prioritizing fallowed croplands for USSE development could preserve rangelands as critical habitat in their current form as grazing lands. Overlap between rangelands and USSE indicates grazed solar arrays.

Consistent with land rent theory, we found that landowner decisions around USSE are based on profit maximization, water availability, agricultural land preservation, and landscape values. Solar interest varies across landowner types, with crop farmers appearing to maximize agriculture-related income and ranchers valuing lifestyle-related landscape benefits that can reduce solar interest. On SJV croplands, lower-income crops facing water constraints are more likely to be replaced with solar facilities than higher-income, permanent crops. The distinct factors informing rancher decisions highlight the importance of recent updates to land rent theory expanding the value of working lands to include ecological and socio-cultural values. These findings are in keeping with past research highlighting the amenity benefits of rangelands as a component of land value (Smith and Martin 1972, Oviedo *et al* 2012, Abrams and Bliss 2013). Given ambitious renewable energy targets, land rent will increasingly include USSE as a diversified source of agricultural income.

These results support several of our hypotheses. USSE contract structure and financing appear to be critical for landowners wary of taking on financial risk. Barriers to USSE deployment include perceived difficulty and landscape values—most notably amenity values and agricultural land preservation ethic. Regarding farm and farmer characteristics, the type of commodities produced, intensity of energy use, and income volatility appear to influence USSE interest.

Our findings highlight several distinctions between peri-urban and rural landowners as found in previous research. Studies have found both rural and urban ranchers to place high value on conservation (Aoyama and Huntsinger 2019), with development pressure and amenity ownership in peri-urban areas potentially reducing conservation commitment (Liffmann *et al* 2000). Similarly, Carlisle *et al* (2014) found rural communities to support nearby USSE more than non-rural communities. In line with these findings, we found SJV ranchers to support USSE more than SFBA ranchers, with SFBA ranchers expressing greater viewshed concerns. Reduced USSE interest among SFBA ranchers may be partly explained by the smaller average property size of interviewed SFBA ranches (746 ha) than SJV ranches (2,983 ha), as larger property owners may be more willing to dedicate a subset of their property to USSE.

These conclusions highlight several opportunities. First, given the relevance of water availability to USSE adoption, groundwater and surface water availability could be integrated into GIS-based studies to account for expected farmland retirement. For example, extensive land fallowing in the Westlands Water District (SJV) has resulted in new USSE being developed in the region, an area highlighted by researchers as ideal for solar development (Butterfield *et al* 2013, Phillips and Cypher 2019) (figure 5). Beyond targeting water-constrained lands, financing and tax credits enable landowner adoption of USSE and therefore should remain a key strategy in state renewable energy policy. As many landowners would dedicate only a subset of their lands to solar energy production, there may be benefit in aggregating USSE on low-fertility lands across neighboring operations in water-constrained areas. The extent of USSE that should be sited on croplands versus rangelands deserves additional investigation given the benefits and drawbacks of each, and the potential types of cropland impacted by solar development (figure 6). In the context of expected farmland retirement, USSE expansion could be expedited by addressing the landowner concerns highlighted here.

Finally, agrivoltaics may offer several important benefits, including improved shade and forage access for livestock (Maia *et al* 2020, Andrew *et al* 2021), drought and heat tolerance for both crops and livestock (Barron-Gafford *et al* 2019), yields (Dinesh and Pearce 2016), community acceptance of USSE (Pascaris *et al* 2021), forage quality (Andrew *et al* 2021), water-use efficiency (Adeh *et al* 2018), and landowner income (Makhijani 2021). Yet

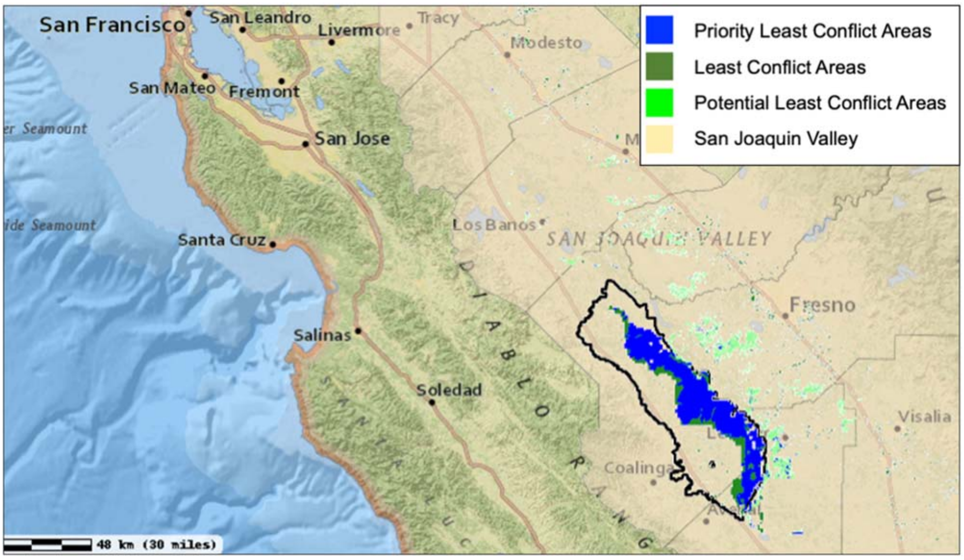

Figure 5. Westlands Water District (outlined in black) is a prime area for USSE development given farmland retirement and low-impact siting opportunities. The areas colored in blue and green were identified by Pearce *et al* (2016) to guide solar development in the SJV. Source: Conservation Biology Institute Data Basin.

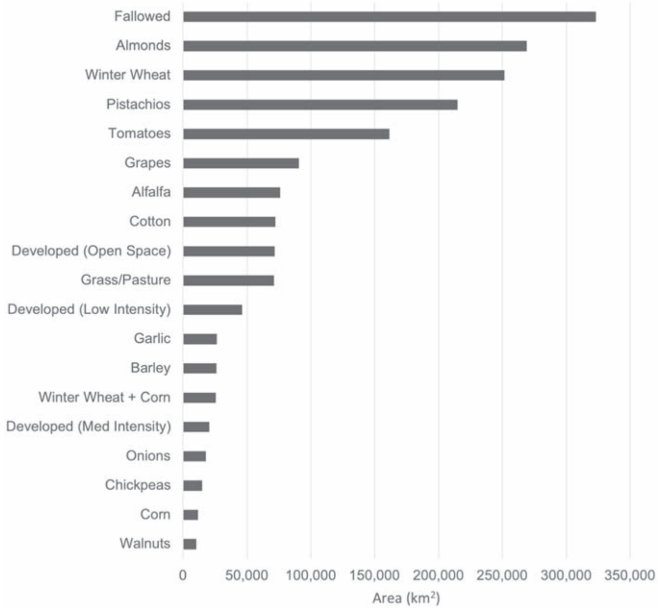

Figure 6. Land cover types and crops impacted by predicted USSE development in the San Joaquin Valley in the least conflict scenario developed by Pearce *et al* (2016). Determined by intersecting the USDA CropScape raster dataset with the Least Conflict Shapefile produced by the Conservation Biology Institute using QGIS. Sources: USDA CropScape 2020 (USDA-NASS 2020), CBI Least Conflict Composite Area—San Joaquin Valley, California (CBI 2015).

the current feasibility of agrivoltaics at the operation scale appears low, with potential negative impacts on the land use efficiencies of both energy and food production.[5] Multifunctional landscapes like agrivoltaic systems can offer ecological benefits but are also a burden on both landowners and solar developers. Upscaling agrivoltaics may require programs that make the trade-offs between agriculture and energy production worthwhile for landowners. County guidance around agrivoltaics and USSE varies, with some counties developing new requirements that agrivoltaics be integrated into USSE projects on agricultural lands. Future research could investigate how agrivoltaics are defined for policymaking, interactions between solar energy and various types of agricultural operations, and challenges around grazing livestock under USSE.

[5] New technological advances may address the decreased productivity and increased costs associated with agrivoltaics.

6. Conclusion

Given the expected role of working lands in hosting new USSE development, a nuanced understanding is needed of how solar facilities interact with agricultural economies and communities. Through our qualitative case study of landowner decisions, we identified operation types that benefit from hosting USSE, challenges to integrating solar facilities into working landscapes, and knowledge gaps. Landowner decisions are informed by profit maximization, water access, landscape values, and agricultural land preservation ethic; rancher decision-processes are distinct from those of crop farmers. USSE offers landowners a promising source of income and opportunity to offset volatility in commodity markets, reduce the burden of energy costs, and manage water-related risk. These findings are relevant to state and regional planning around renewable energy, conservation, and agriculture. In particular, state energy agencies should target areas with declining water availability—and therefore low agricultural potential—for energy infrastructure development. Prioritizing USSE on these retired croplands would likely decrease displacement of food production and impacts on rangeland habitat. Although integrating cattle grazing into solar arrays could expand land availability for USSE and improve the habitat value of solar arrays, this approach is also challenged by increased costs and management complexity.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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